

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
13 September 2001 (13.09.2001)

PCT

(10) International Publication Number
WO 01/67057 A1

- (51) International Patent Classification⁷: **G01K 11/00**
- (21) International Application Number: PCT/GB01/01043
- (22) International Filing Date: 9 March 2001 (09.03.2001)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
0005926.1 10 March 2000 (10.03.2000) GB
- (71) Applicant (for all designated States except US): **THE UNIVERSITY COURT OF THE UNIVERSITY OF GLASGOW** [GB/GB]; Gilbert Scott Building, University Avenue, Glasgow G12 8QQ (GB).
- (72) Inventor; and
- (75) Inventor/Applicant (for US only): **LAND, David, Victor** [GB/GB]; 22 Rowallan Gardens, Glasgow G11 7LG (GB).
- (74) Agents: **McCALLUM, William, Potter et al.**; Cruikshank & Fairweather, 19 Royal Exchange Square, Glasgow G1 3AE (GB).

(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

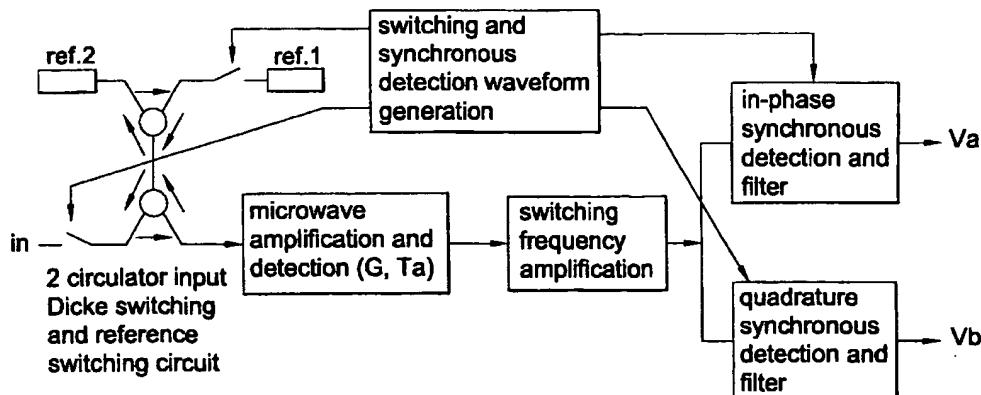
(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: IMPROVED TEMPERATURE MEASURING APPARATUS



(57) Abstract: There is disclosed an improved apparatus (5) for measuring a temperature of an object (14) such as a food product. Also disclosed are a related method, container (20), transportation means (25), and production line. The apparatus (5) comprises: means for coupling radiation emanating from the object (14) to at least a first radiation temperature measuring radiometer (11); and first means for switching measurement circuiting between measuring a radiation temperature of at least a first reference temperature source and a radiation temperature of the object (14).

WO 01/67057 A1

-1-

IMPROVED TEMPERATURE MEASURING APPARATUS

FIELD OF INVENTION

This invention relates to a temperature measuring apparatus. The invention in particular, though not exclusively, relates to the use of microwave radiometry in the measurement of temperature. In particular further, though not exclusively, the present invention relates to use of microwave radiometry in monitoring temperature of a sample, such as a food product during processing, eg production, cooking, packaging, storing, freezing, defrosting, or the like.

BACKGROUND OF INVENTION

The food industry in particular, requires a non-invasive, non-destructive temperature measuring technique for process monitoring, product safety and quality control. Typical requirements are to check that a food product has been cooked, or at least partly cooked, to a specified minimum temperature, or cooled to below a specified temperature, eg for storage or distribution. At present, the only useful technique is invasive probing by thermocouple or thermistor temperature sensors. The product so tested must be discarded after probing. Such a technique is therefore necessarily a sampling technique where the chosen samples are wasted. The temperature measured by probing therefore also only applies to a small volume of material around the probe, and the probing is subject to significant operator-dependent variability.

The present invention seeks to employ microwave radiometric temperature measurements which are inherently non-invasive and non-destructive. This allows potentially a whole production batch to be monitored, with no financial penalty, which can improve the efficiency of the process and the quality and safety control of the product.

-2-

It is desired that the microwave temperature measurement be made in a way that is independent of an operator, not be influenced by electromagnetic radiation external to the product being measured, and be dependent on the temperature within or throughout the bulk of the product material. Electromagnetically enclosed cavities/cavity-antennas provide a way of coupling the microwave thermal radiation from a product to the radiation temperature measuring radiometer receiver that meets these requirements. The radiometric temperature of the signal from the cavity/cavity antenna must be measured by a microwave radiometer capable of measuring the temperature over the range required for the application, with an accuracy, resolution and response time appropriate to the application.

It is also desired to employ microwave radiometry requiring:

(a) Good microwave temperature measurement accuracy over an increasingly wide temperature range (comparable to good electrical thermometry), eg +/-0.5°C from -20°C to 100°C for food product.

(b) High microwave temperature measurement accuracy over the bio-medical temperature range (eg +/-0.1°C from 30°C to 43°C).

(c) An ability to determine the proper matched-impedance radiometric temperature of a source connected to the radiometer in the presence of impedance mis-match reflections between the source and the radiometer.

(d) An ability to make a determination of the proper matched-impedance radiometric temperature of a source connected to the radiometer with a uniform frequency response over the measurement bandwidth.

This is highly desirable for measuring sources that may have a non-uniform radiation spectrum within the measurement bandwidth.

In one aspect the radiometer design requires to

-3-

determine the source temperature independently of the gain of the microwave amplification, detection, and post-detection amplification. Strictly this may be the gain between a radiometer input ("Dicke") switch and the post-detection synchronous demodulation. Implicitly the gain dependence contains frequency response independence (just gain at a given frequency). Gain stability and frequency response uniformity are, however, required between the input ("Dicke") switch and the two reference sources.

5 These are, however, passive microwave circuit paths and these requirements can be provided by practical microwave components.

10

It may also be desired to provide the following requirements:

15 (e) A need to measure radiometric temperatures at different frequencies to estimate temperature profiles within source materials.

20 (f) A need for radiometric temperatures measured at different frequencies to be accurately related to each other (application dependent but to less than 0.1°C for medical applications and to less than 0.5°C for industrial applications).

25 It is an object of at least one aspect of the present invention to obviate or at least mitigate one or more of the aforementioned problems.

It is a further object of at least one aspect of the present invention to seek to provide one or more of the aforementioned requirements.

30 The above-mentioned measurements need to be made with the best response-time temperature resolution that microwave radiometry is inherently capable of (ie The "Gabor limit"). For industrial applications the measuring radiometer must also operate in a wide range of ambient temperatures (e.g. from about -10°C to about 40°C without significant degradation of measurement accuracy). Further, 35 the radiometer should not require frequent calibration.

-4-

SUMMARY OF INVENTION

According to a first aspect of the present invention there is provided an apparatus for measuring a temperature of an object comprising:

5 means for coupling radiation emanating from the object to at least a first radiation temperature measuring radiometer; and

10 first means for switching measurement circuitry between measuring a radiation temperature of at least a first reference temperature source and a radiation temperature of the object.

Preferably, there are provided means for establishing a standing wave pattern of the radiation from the object.

15 In this way the apparatus may be used to efficiently collect and couple (natural) thermal radiation emanating from the object being measured.

Preferably, the radiation is in the microwave region.

Preferably, the microwave radiation has a frequency in the range of 0.1GHz to 30GHz.

20 Preferably, there are provided means for coupling the radiation to a second radiometer.

25 Preferably, there are provided second means for switching measurement circuitry between the temperature signal of at least a second reference temperature source and the temperature of the object.

Preferably, there are provided first and second switching means which operate out of phase with one another.

30 Preferably, signals from the first and second switching means are demodulated at a switching frequency of the first switching means. This may be used as a means of computing/finding a ratio of the in-phase to quadrature signals. This may be obtained by using, for example, analogue electronic "synchronous detector" circuits, or by 35 numerical (digital) signal processing after analogue to

-5-

digital signal conversion.

According to a second aspect of the present invention there is provided a method for measuring a temperature of an object comprising:

5 coupling radiation emanating from the object to at least a first measuring radiometer;

switching measurement circuitry between a signal representative of temperature of at least a first reference temperature source and a signal representative of 10 temperature of the object.

Preferably, the method also comprises a preceding step of establishing a standing wave pattern of radiation emanating from the object.

In this way the method may be used to efficiently 15 collect and couple (natural) thermal radiation from the object being measured to the measurement circuitry.

According to a third aspect of the present inventions, 20 there is provided a container such as a transportation container, including an apparatus for measuring a temperature of an object according to the first aspect.

According to a fourth aspect of the present invention, there is provided a transportation means including an apparatus for measuring a temperature of an object according to the first aspect.

25 According to a fifth aspect of the present invention there is provided an apparatus for measuring a temperature of an object comprising:

means for coupling radiation emanating from the object to at least a first radiometer;

30 first means for switching measurement circuitry sequentially between signals representative of temperatures of at least two different reference temperature sources and a signal representative of a temperature of the object; and

35 means for splitting a signal from the switching means between at least two frequency selective channels.

- 6 -

In this way the apparatus may be used to efficiently collect and couple (natural) thermal radiation emanating from the object being measured. Furthermore, in this way, one may provide one or more frequency dependent radiometric temperatures and via demodulation a ratio for each channel.

5 Preferably, there are provided means for establishing a standing wave pattern of the radiation from the object.

Preferably, the radiation is in the microwave region.

10 Preferably, the microwave radiation has a frequency in the range of 0.1GHz to 30GHz.

15 Preferably, there are provided demodulation means for demodulating the switched signals after amplification and detection and computing the ratio of in-phase and phase-quadrature components relative to the sequential switching by synchronous demodulation at a frequency of operation of the first switching means.

According to a sixth aspect of the present invention there is provided a method of measuring a temperature of an object comprising:

20 coupling radiation emanating from an object to at least a first radiometer;

25 switching measurement circuitry sequentially between signals representative of temperatures of at least two different reference temperature sources and a signal representative of the temperature of the object; and

splitting a signal from the switching means between at least two frequency selective channels.

30 In this way, the method may be used to efficiently collect and couple (natural) thermal radiation from the object being measured. Furthermore, in this way one may provide one or more frequency dependent radiometric temperatures and via demodulation a ratio for each channel.

35 Preferably, the method also comprises the initial step of establishing a standing wave pattern of radiation emanating from the object.

According to a seventh aspect of the present

-7-

invention, there is provided a container such as a transportation container including an apparatus for measuring a temperature of an object according to the fifth invention.

5 According to an eighth aspect of the present invention, there is provided a transportation means including an apparatus for measuring a temperature of an object according to the fifth aspect.

10 According to a ninth aspect of the present invention there is provided an apparatus for measuring a temperature of an object comprising:

means for coupling radiation emanating from the object to at least two radiometers each having at least one reference temperature signal source; and

15 means for controlling the radiometers such that when one radiometer is detecting the radiation another one of the radiometers is detecting the at least one reference temperature signal source the said one radiometer is detecting the at least one reference temperature signal source the said another one of the radiometers is detecting the radiation.

20 At least two measurements are therefore available in the same time as one measurement would be for an apparatus having only one radiometer. This may be beneficial in increasing a throughput of objects to be temperature measured, eg in a high volume production line or the like.

25 The apparatus may also enable efficient collection and coupling of (natural) thermal radiation emanating from the object being measured.

30 Preferably, the thermal radiation emanating from the object is used to set up a standing wave pattern.

Preferably, the radiation is in the microwave region.

Preferably, the microwave radiation has a frequency in the range of 0.1GHz to 30GHz.

35 Preferably, the radiometers are Dicke or comparator type radiometers.

-8-

The reference temperature signal source of each radiometer may have the same source or may have different sources.

5 Preferably, each of the one and another radiometers have the same switching frequency between the radiation and the reference temperature signal source.

Preferably, the one and the another radiometers are 180° out of phase with one another, in operation.

10 According to a tenth aspect of the present invention there is provided a method for measuring a temperature of an object comprising:

coupling radiation emanating from an object to at least two radiometers each having at least one reference temperature signal source; and

15 controlling the radiometers such that when one radiometer is detecting the radiation another one of the radiometers is detecting the at least one reference temperature signal and when the said one radiometer is detecting the at least one reference temperature source the said another one of the radiometers is detecting the radiation.

In this way, the apparatus may be used to efficiently collect and couple (natural) thermal radiation emanating from the object being measured.

25 According to an eleventh aspect of the present invention there is provided a container such as a transportation container including an apparatus for measuring a temperature of an object according to the ninth aspect.

30 According to a twelfth aspect of the present invention there is provided a transportation means including an apparatus for measuring a temperature of an object according to the ninth aspect.

35 According to a thirteenth aspect of the present invention there is provided a production line including an apparatus for measuring a temperature of an object

-9-

according to the first, fifth or ninth aspects.

According to a fourteenth aspect of the present invention there is provided a radiometer device comprising:

5 at least two radiometers each having at least one reference temperature signal source and means for controlling the at least two radiometers such that when one radiometer is detecting radiation another one of the radiometers is detecting the at least one reference temperature signal and when the said one radiometer is 10 detecting the at least one reference temperature source the said another one of the radiometers is detecting radiation.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the present invention will now be described, by way of example only, and with reference to 15 the accompanying drawings which are:

- Figure 1 a schematic perspective view of an apparatus for measuring a temperature of an object given by way of illustration for use in a number of embodiments of the present invention, the illustrative apparatus including a cavity;
- 20 Figure 2 a graph of electric field and power for $l=1$, $m=1$ and $n=0$ (with l , m , n being integral numbers which define the form of the standing wave patterns in the 3 dimensions of the cavity of the apparatus of Figure 1);
- 25 Figure 3 a graph of electric field and power for $l=1$, $m=1$, and $n=1$;
- Figure 4 a schematic diagram of a single frequency two-reference radiometer capable of use with the apparatus of Figure 1 in embodiments of the present invention;
- 30 Figure 5 a schematic diagram of multi-frequency two-reference radiometer capable of use with the

-10-

apparatus of Figure 1 in further embodiments
of the present invention; and
Figure 6
5 a schematic diagram of a radiometer capable
of use with the apparatus of Figure 1 in or
still further embodiments of the present
invention, the radiometer being adapted for
analysis of a signal from the cavity.

DETAILED DESCRIPTION OF DRAWINGS

Referring initially to Figure 1 an apparatus generally
10 designated 5 according to a first embodiment of the present
invention, for measuring a temperature of an object or
product 14, such as a food product, comprises:

means for coupling radiation emanating from the object
14 to at least a first radiation temperature measuring
15 radiometer 11; and

first means for switching measurement circuiting
between measuring a radiation temperature of at least a
first reference temperature source and a radiation
temperature of the object 14.

As can be seen from Figure 1, the apparatus 5 includes
a walled structure 6 defining a cavity 10 wherein the
object 14 is received the cavity having a coupling port 12.

The apparatus 5 represents a typical apparatus according
to the present invention used to monitor the temperature of
25 an object 14 using natural emanating microwave radiation
from the object 14. The coupling port 12 electro-
magnetically connects the cavity 10 to one or more
radiation signal measuring radiometer receivers (forming an
"antenna-cavity" structure).

The cavity 10 is made from a suitable conductive
material such as copper, copper plated steel and silver
plated brass. These materials are chosen because they have
good microwave surface conductivity. The enclosing of the
measurement region provides isolation from external sources

-11-

of electro-magnetic radiation allowing proper measurement of the effective radiation temperature of an object 14 within the cavity 10. As can be seen from Figure 1, the object 14 is substantially centrally placed within the casing 10.

A suitable size of cavity 10 is 0.25m x 0.25m x 0.15m. However, a wide range of sizes from a few millimetres to a few metres can be used depending on the frequency and mode of measurement. It is, for example, in an embodiment of the present invention possible to monitor a temperature of an object 14 within the apparatus 5 which apparatus can comprise a transport container 20 on a transportation means 25 such as a lorry, or a train, or ship, or the like. Alternatively the apparatus 5 can comprise part of a production line 25.

In use, to measure the temperature of the object 14 a microwave standing wave pattern of naturally occurring microwaves from the object 14 is set-up inside the cavity 10. The microwaves are typically in the wavelength region 0.1 GHz to 30 GHz.

An apparent radiation temperature seen by a radiometer 11 connected to the cavity 10 will be substantially that of the material of the object 14 within the cavity 10 weighted according to a weighting function applying to the whole source (cavity and product). By weighting function is meant that although the temperatures across the whole cavity 10 contribute to the obtained measured temperature, the temperature reading is biased due to the standing wave arrangement in the cavity 10 towards a certain region of the cavity 10. Therefore, by altering the properties of the standing wave pattern different regions of the object 14 within different parts of the cavity 10 can have their temperature measured. In general, if the radiation losses of the object 14 are much larger than the losses in the enclosing/coupling antenna-cavity structure 10, the measured temperature will be close to that of the object 14

-12-

and the antenna-cavity temperature has only a small effect.

Referring to Fig. 2 there are shown field and power density profiles across the cavity 10 for a given frequency of radiation. It can be clearly seen that the signal is
5 strongest in the centre of the cavity 10 and, therefore, the temperature reading will be predominantly biased by the temperature in that region. To measure the temperature of the object 14, the object 14 should therefore be placed in the centre of the measurement region. The arrangement in
10 Fig. 2 therefore provides a centrally weighted microwave temperature measurement.

It should be noted that in Fig. 2 a uniform Z-field is used and there is therefore, no variation in the vertical direction. (If the Z-field was varied a 3-D topographic
15 surface would be obtained for the electric field and power density).

Fig. 3 shows electric field and power density profiles for a further given frequency of higher frequency than the given frequency of Fig. 2. In Fig. 3, the obtained
20 temperature reading, therefore, tends towards a "quasi-uniform" response across the whole of the cavity 10 tending to give an "average" temperature for the object 14 within the cavity 10.

Referring to Figures 4, 5 and 6, there are illustrated
25 radiometers, generally designated 111, 211, 311 respectively, which may be used in this first embodiment of the present invention.

Figure 4 illustrates a radiometer 111, having two reference temperature sources. The ratio V_a/V_b gives the
30 gain (G), amplifier noise temperature T_a , and input reflection coefficient independent "R" value used to calculate the source microwave radiometric temperature. The reference temperatures used with R for the calculation are obtained from direct, contact temperature measurements
35 on the reference loads using the instrument calibration.

The microwave (or radio) frequency radiometer 111 uses

-13-

a switch+circulator input circuit to switch between the object 14 to be measured and a reference temperature source which can be switched to, for example, two different values of reference temperature. At any point after the source 5 reference switch but before high-frequency detection, the signal is switched between two or more frequency selective channels of amplification and detection. Each of the post-detection signals is then demodulated into in-phase and phase-quadrature components relative to the switching 10 sequence by synchronous demodulation at the switching frequency. The ratio of each pair of in-phase to the phase-quadrature signals is taken along with non-high-frequency measurements and calibration information which gives reference temperature values, to compute an equivalent temperature of the source signal for each of 15 selected frequency ranges. The value of each of the post-detection signal ratios is independent of any source to radiometer reflection and independent of amplification (gain and frequency response) between the source-reference 20 switch and the synchronous demodulation. Each computed temperature is thus reflection independent and amplification gain independent. Each frequency dependent signal and computed source temperature is referenced to the same two temperature reference sources and the source and 25 reference signals pass through the same radiometer input circuit components for all frequencies measured.

The use of a source-reference switching sequence is advantageous in that synchronous post-detection demodulation combined with the use of frequency selective 30 amplification and detection allows simultaneous "real time" values of frequency dependent radiometric temperature for a source.

The use of two reference temperatures chosen to be above and below the main measurement temperature gives good 35 temperature measurement accuracy. The use of the synchronous source-reference switching sequence and the

-14-

post-detection signal demodulation combined with post-source-reference switching frequency selection allows continuous and simultaneous "real time" multifrequency temperature measurements with measurement times and 5 temperature resolutions appropriate to a particular applications requirements. Each temperature value determined by the radiometer 111 is independent of any reflection between the source object 14 and the radiometer 111 and is independent of the ambient temperature 10 sensitive amplification gain in the high-frequency parts of the radiometer 111. Since each frequency dependent signal and computed source temperature is referenced to the main two temperature reference sources, an excellent intercalibration accuracy is achieved.

15 Figure 5 illustrates a radiometer 211 comprising a multi-frequency two-reference radiometer having two-reference temperature sources ref 1 and ref2. The radiometer 211 is a practical 3-band radiometer using microwave switches, circulator and reference loads 20 operating over 2 - 4 GHz, feeding a low-noise 2 - 4 GHz microwave amplifier after the circulator. After the amplifier the signal is split into 3 channels of filters, amplifiers and detectors at, for example, 2.0 - 2.4 GHz, 2.8 - 3.2 GHz and 3.6 - 4.0 GHz. After post-detection 25 demodulation computation the radiometer 211 provides the equivalent microwave temperatures of the object 14 centred on 2.2, 3.0 and 3.8 GHz.

Figure 6 illustrates a radiometer 311 having two-reference temperature sources, Tref 1 and Tref 2. The radiometer 311 includes various component sections for 30 analysis of a radiation temperature signal from cavity 10.

The radiometric signal from the source antenna-cavity goes first to a circuit comprising two electronic microwave switches ("PIN switch" for PIN-diode switch), two microwave 35 circulators (the "dual circulator") and two microwave

-15-

matched impedance loads (marked "load"). When the switches are closed (shorting to ground in the particular configuration shown) microwave signals are efficiently reflected from them. When they are open (for the configuration shown) microwave signals are efficiently transmitted past them. The circulators allow microwave signal transmission from port to port around the radiometer 311 in a specified direction or order (e.g. port 1 to 2 to 3 to 1; not 3 to 2 to 1 to 3). The matched impedance microwave loads are fitted with temperature measuring sensors which, following calibration, allows them to provide accurately known thermal (ie radiometric) signals to the microwave circuits to which they are connected. The switches are operated sequentially to provide source-reference signals needed for the operation of the radiometer 311, (e.g. the source switch is open and shut for accurately equal lengths of time over one switching cycle, eg 1 millisecond, and within each open or closed half of the cycle the reference switched with accurately equal open and shut times - 0.25 milliseconds for this case). This circuit then provides a timed sequence of four radiometric temperatures of essentially the form: source + reference 1 + circuit noise; source + reference 2 + circuit noise; reference 1 + circuit noise; reference 2 + circuit noise. The temperature of the microwave switching circuit components may be monitored to calculate the effective radiometric reference temperatures with improved accuracy.

The sequence of radiometric temperature signals from the switching circuit is amplified, filtered to define the frequency range for measurement, and high-frequency detected to provide a signal at the switching frequency and its harmonics (at 1kHz and low order harmonics for this case). This signal is amplified and passed to in-phase and quadrature phase-sensitive or synchronous demodulators to extract the in-phase and quadrature components which are then passed through low-frequency low pass filters. The

-16-

resulting voltages are passed to analogue to digital converters and a computing system, which calculates the radiometric temperature of the source signal from the ratio of these voltages and the measured temperatures of the reference loads and calibration information. The remaining circuitry generates accurately time switched waveforms for the microwave switches and the synchronous demodulators.

Referring again to Figure 1 an apparatus, generally designated 5 according to a second embodiment of the present invention, for measuring a temperature of an object or product 14, such as a food product, comprises:

means for coupling radiation emanating from the object 14 to at least a first radiometer;

first means for switching measurement circuitry sequentially between signals representative of temperatures of at least two different reference temperature sources and a signal representative of the temperature of the object 14; and

means for splitting a signal from the switching means between at least two frequency selective channels. In this way one may provide one or more frequency dependent radiometric temperatures and via demodulation, a ratio for each channel. The results obtained are therefore independent of the radiometer used to perform the measurements.

The microwave (or radio) frequency radiometer 11 uses a switch+circulator input circuit to switch between the source to be measured and a reference temperature source which can be switched to two different values of reference temperature. The source-reference switching sequence is such that after high-frequency amplification and detection, the post-detection signal can be resolved into in-phase and phase-quadrature components relative to the switching sequence by synchronous demodulation (i.e. detection) at this switching frequency. The ratio of the in-phase to phase-quadrature signals taken along with non-high-

-17-

frequency measurements and/or calibration information to obtain the reference temperature values, allows the equivalent matched-impedance noise temperature of the source signal to be computed. The value of the post-detection signal component ratio is independent of any source to radiometer impedance mis-match reflection. This ratio is also independent of signal amplification (gain and frequency response) between the source-reference switch and the synchronous demodulation. The computed temperature is thus reflection independent and amplification gain independent.

The use of a source-reference switching sequence is advantageous in that the source/reference switching sequence (pattern) combined with in-phase and quadrature demodulation at the switching frequency provides two signals whose ratio is reflection and gain independent. The signal is computed from the post synchronous demodulation signals.

The use of two reference temperatures chosen to be above and below the main measurement range gives good temperature measurement accuracy. The use of the synchronous source-reference switching sequence and the post-detection signal demodulation allows continuous "real time" temperature measurement with measurement times and temperature resolutions appropriate to that of a specific application's requirement. The temperature value determined by the radiometer 11 is independent of any reflection between the source and the radiometer 11. The temperature value determined by the radiometer 11 is independent of the ambient temperature sensitive amplification gain in the high-frequency part of the radiometer 11.

Referring to Figures 4, 5, and 6, there are illustrated radiometers, generally designated 111, 211, 311 respectively, which have hereinbefore been described and which may be used in this second embodiment of the present invention.

-18-

In the radiometer 111 of Figure 4, the ratio of the in-phase synchronous detection and the quadrature synchronous detection is used to calculate the source microwave radiometric temperature.

5 Referring yet again to Figure 1 an apparatus, generally designated 5 according to a third embodiment of the present invention, for measuring a temperature of an object or product 14, such as a food product, comprises:

10 means for connecting or coupling to (natural) thermal radiation from the object 14 being measured; means for coupling the radiation to at least two radiometers 11,11',11", each having at least one reference temperature signal source; and means for controlling the radiometers 11,11',11" such that when one radiometer 11 is measuring 15 the object radiation temperature signal another one of the radiometers 11',11" is measuring the at least one reference temperature signal source and when the said one radiometer 11 is measuring the reference temperature signal source the said another one of the radiometers 11',11" is measuring 20 the object radiation temperature signal.

The radiometers 11,11',11" may comprise two Dicke or comparator type radiometers which are to some degree electro-magnetically coupled to through use of a common antenna cavity structure. The radiometers 11,11',11" may 25 use a common coupling port 12 or separate coupling ports 12,12', probe or loop structures. The radiometers 11, 11', 11" may be any form of Dicke radiometers using one or two reference temperature sources, but the source-reference switching advantageously have the same frequency and equal 30 source and reference connection times (1:1 source:reference ratio). If the source switching of the radiometer 11, 11', 11" is in synchronism in-phase, both radiometers 11,11',11" will be coupled to the source region simultaneously. This overcomes the problem where if the two 35 radiometers 11,11' or 11,11" are not switched synchronously wherein there will be times when both radiometers 11,11' or

-19-

11,11" are simultaneously coupled to the source region. (At
the difference ("beat") frequency between the two
frequencies). In this situation each radiometer 11,11',11"
will, at these times, tend to couple through the common
5 source region to the noise signal from the input circuit of
the other radiometer. Each radiometer 11,11',11" will then
measure a radiometric temperature that is a combination of
the wanted source temperature and the noise temperature of
the other radiometer input circuit. The error due to the
10 input circuit noise coupling will, in general, be ill-
controlled and be particularly dependent on source material
to coupling structure interactions. If the radiometer to
source region couplings are designed to couple at different
15 frequencies or to different source region field patterns
(standing wave modes/radiometric weighting functions), this
will provide some reduction in the radiometer cross-
coupling but will not, in practice, eliminate it. The
present embodiment involves synchronised radiometer
switching cycles with a half-cycle (180° phase) difference,
20 when a radiometer 11 will be coupled to the measurement
region when the other radiometer 11' or 11" is switched to
its reference source. Except for the insertion losses of
the radiometer input switches when in their referenced
25 positions, this synchronised switching arrangement will
provide full isolation between the radiometers 11, 11' or
11,11". This will allow simultaneous rather than sequential
measurements to be made by the two radiometers 11,11' or
11,11", with total temperature measurement time that of an
individual radiometer.

30 It will be appreciated that the embodiments of the
present invention hereinbefore described are given by way
of example only, and are not meant to limit the scope of
the invention in any way.

35 It will be particularly appreciated that this
invention and particularly the third embodiment
hereinbefore described has advantages in that the

-20-

temperature of an object (sample) may be measured relatively quickly. The apparatus of the invention and particularly the third embodiment is, therefore, highly suitable for a high volume production line.

-21-

CLAIMS

1. An apparatus for measuring a temperature of at least a portion of object comprising:
 - means for coupling radiation emanating from the object to at least a first radiation temperature measuring radiometer; and
 - first means for switching measurement circuitry between measuring a radiation temperature of at least a first reference temperature source and a radiation temperature of the object.
2. An apparatus according to Claim 1, including means for collecting and coupling naturally occurring thermal radiation emanating from the object being measured to the measurement circuitry.
- 15 3. An apparatus according to any preceding claim, wherein there are provided means for establishing a standing wave pattern of the radiation from the object.
4. An apparatus according to any preceding claim, wherein the radiation is in the microwave region.
- 20 5. An apparatus according to Claim 4, wherein the microwave radiation has a frequency in the range of 0.1GHz to 30GHz.
6. An apparatus according to any preceding claim, wherein there are provided means for coupling the radiation to a second radiometer.
- 25 7. An apparatus according to any preceding claim, wherein there are provided second means for switching measurement circuitry between a temperature signal of at least a second reference temperature source and the temperature of the

-22-

object.

8. An apparatus according to Claim 7, there are provided first and second switching means which operate out of phase with one another.

5 9. An apparatus according to Claim 8, wherein the signals from the first and second switching means are demodulated at a switching frequency of the first switching means which is used as means of determining a ratio of the in-phase to quadrature signals.

10 10. An apparatus according to Claim 9, wherein the determining means includes or comprises analogue electronic synchronous detector circuitry, or analogue to digital conversion means and numerical (digital) signal processing means.

15 11. A method for measuring a temperature of at least a portion of an object comprising:

coupling radiation emanating from the object to at least a first measuring radiometer;

20 12. A method according to claim 11, which includes collecting and coupling naturally occurring thermal radiation from the object being measured to the switching measurement circuitry.

25 13. A method according to either of claims 11 and 12, which also comprises a preceding step of establishing a standing wave pattern of radiation emanating from the object.

-23-

14. A container including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 1 to 10.

5 15. A transportation means including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 1 - 10.

16. An apparatus for measuring a temperature of at least a portion of an object comprising:

10 means for coupling radiation emanating from the object to at least a first radiometer;

15 first means for switching measurement circuitry sequentially between signalling means representing a temperature of at least two different reference temperature sources and a signalling means representing a temperature of the object; and

means for splitting a signal from the switching means between at least two frequency selective channels.

20 17. An apparatus according to Claim 16, which include means for collecting and coupling naturally occurring thermal radiation emanating from the object being measured to the measurement circuitry.

25 18. An apparatus according to any of claims 16 and 17, which provides one or more frequency dependent radiometer temperature measurements and via demodulation a ratio for each channel.

19. An apparatus according to any of claims 16 to 18, wherein there are provided means for establishing a standing wave pattern of the radiation from the object.

30 20. An apparatus according to any of claims 19 to 19, wherein the radiation is in the microwave region.

-24-

21. An apparatus according to Claim 20, wherein the microwave radiation has a frequency in the range of 0.1GHz to 30GHz.

5 22. An apparatus according to any of Claims 16 to 21, wherein there are provided demodulation means for demodulating the switched signals after amplification and detection and computing the ratio of in-phase and phase-quadrature components relative to the sequential switching by synchronous demodulation at a frequency of operation of
10 the switching means.

23. A method of measuring a temperature of at least a portion of an object comprising:

coupling radiation emanating from an object to at least a first radiometer;

15 switching measurement circuitry sequentially between signalling means representative of temperatures of at least two different reference temperature sources and a signalling means representative of the temperature of the object; and

20 splitting a signal from the switching means between at least two frequency selective channels.

24. A method according to Claim 23 which includes collecting and coupling naturally occurring thermal radiation from the object being measured.

25 25. A method according to any of Claims 23 and 24, which includes providing one or more frequency dependent radiometric temperature measurements and via demodulation a ratio for each channel.

30 26. A method according to any of claims 23 to 25, which comprises a preceding step of establishing a standing wave pattern of radiation emanating from the object.

-25-

27. A container including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 16 to 22.

5 28. A transportation means including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 16 to 22.

29. An apparatus for measuring a temperature of at least a portion of an object comprising:

10 means for coupling radiation emanating from the object to at least two radiometers each having at least one reference temperature signal source; and

15 means for controlling the radiometers such that when one radiometer is detecting the radiation another one of the radiometers is detecting the at least one reference temperature signal and when the said one radiometer is detecting the at least one reference temperature source the said another one of the radiometers is detecting the radiation.

20 30. An apparatus according to claim 29 which includes means for allowing throughput of objects to be temperature measured.

25 31. An apparatus according to either of Claims 29 or 30 which includes means for enabling collection and coupling of naturally occurring thermal radiation emanating from the object being measured.

32. An apparatus according to any of Claims 29 to 31, wherein, in use, thermal radiation emanating from the object is used to set up a standing wave pattern.

30 33. An apparatus according to any of Claims 32, wherein the radiation is in the microwave region.

-26-

34. An apparatus according to Claim 33, wherein the microwave radiation has a frequency in the range of 0.1GHz to 30GHz.

5 35. An apparatus according to any of Claims 29 to 34, wherein the radiometers are Dicke or comparator type radiometers.

36. An apparatus according to any of Claims 29 to 35, wherein the reference temperature signal source of each of the radiometers is the same source.

10 37. An apparatus according to any of Claims 29 to 35, wherein the reference temperature signal source of each radiometer has a different source.

15 38. An apparatus according to any of Claims 29 to 37, wherein each of the one and another radiometers have the same switching frequency between the radiation and the reference temperature signal source.

20 39. An apparatus according to any of Claims 29 to 35, wherein the one and the another radiometers are substantially 180° out of phase with one another, in operation.

40. A method for measuring a temperature of at least a portion of an object comprising:

25 coupling radiation emanating from an object to at least two radiometers each having at least one reference temperature signal source; and

30 controlling the radiometers such that when one radiometer is detecting the radiation another one of the radiometers is detecting the reference temperature signal and when the said one radiometer is detecting the reference temperature source the said another one of the radiometers

-27-

is detecting the radiation.

41. A method according to Claim 37, which includes collecting and coupling naturally occurring thermal radiation emanating from the object being measured.

5 42. A container including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 29 to 39.

10 43. A transportation means including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 29 to 39.

44. A production line including an apparatus for measuring a temperature of at least a portion of an object as claimed in any of Claims 1 to 10, Claims 16 to 22, or Claims 29 to 39.

15 45. A radiometer device comprising:
at least two radiometers each having at least one reference temperature signal source and means for controlling the at least two radiometers such that when one radiometer is detecting radiation, another one of the radiometers is detecting the reference temperature signal and when the said one radiometer is detecting the reference temperature source the said another one of the radiometers is detecting radiation.

20 25 46. An apparatus for measuring a temperature of an object as hereinbefore described with reference to the accompanying drawings.

47. A method of measuring a temperature of an object as hereinbefore described with reference to the accompanying drawings.

-28-

48. A container as hereinbefore described with reference to the accompanying drawings.

49. A transportation means as hereinbefore described with reference to the accompanying drawings.

5 50. A production line as hereinbefore described with reference to the accompanying drawings.

1/6

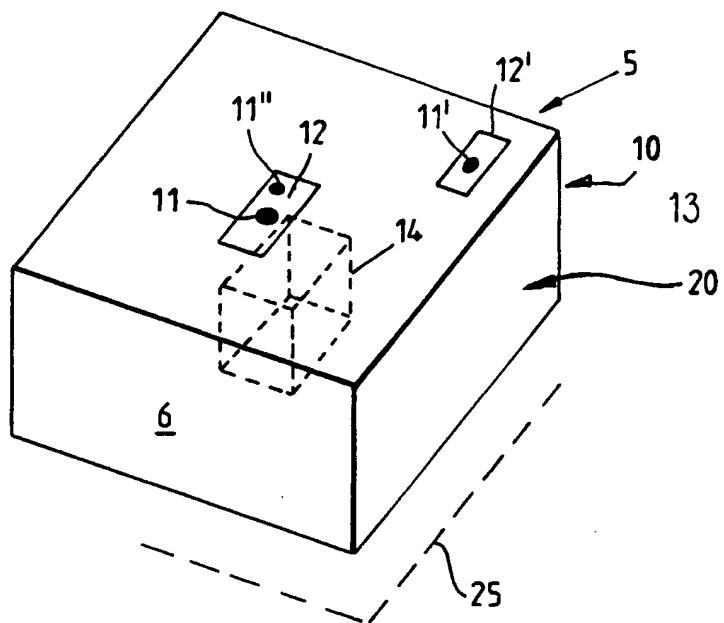
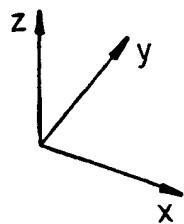


Fig. 1

2/6

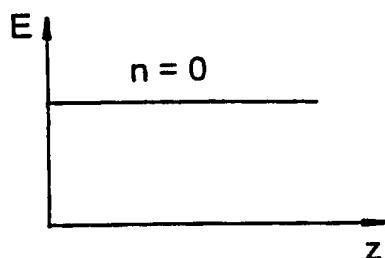
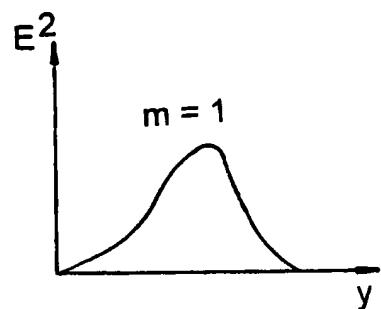
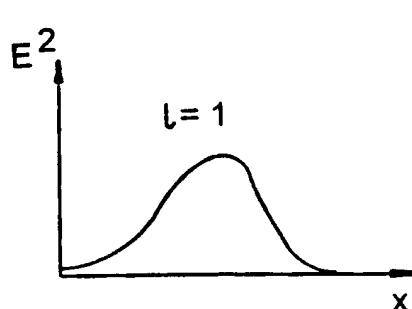
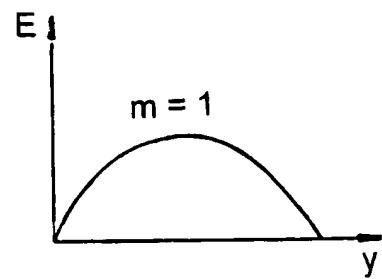
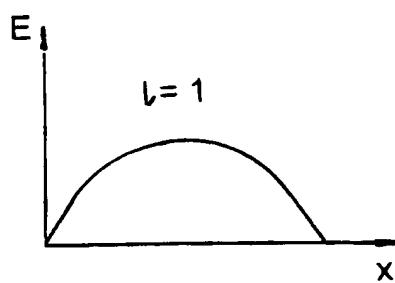


Fig. 2

3/6

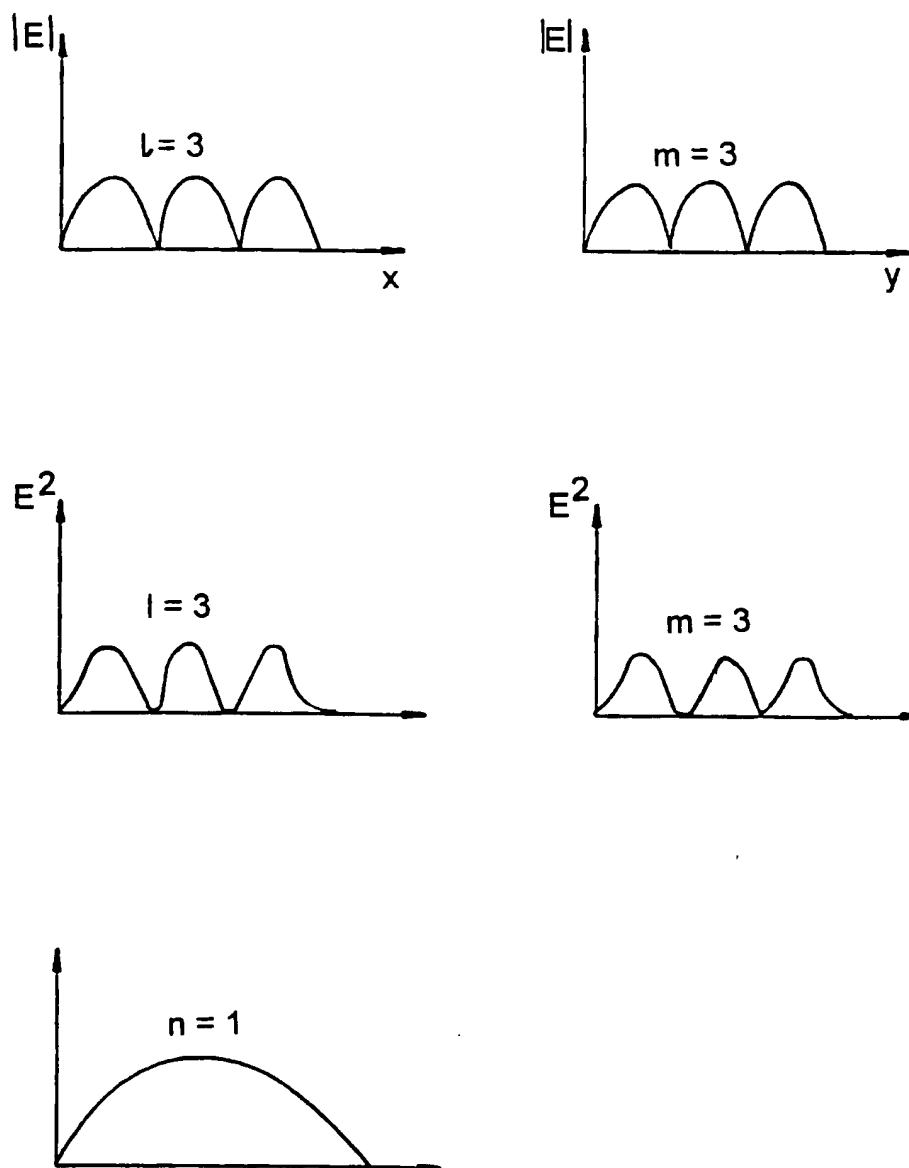


Fig. 3

4/6

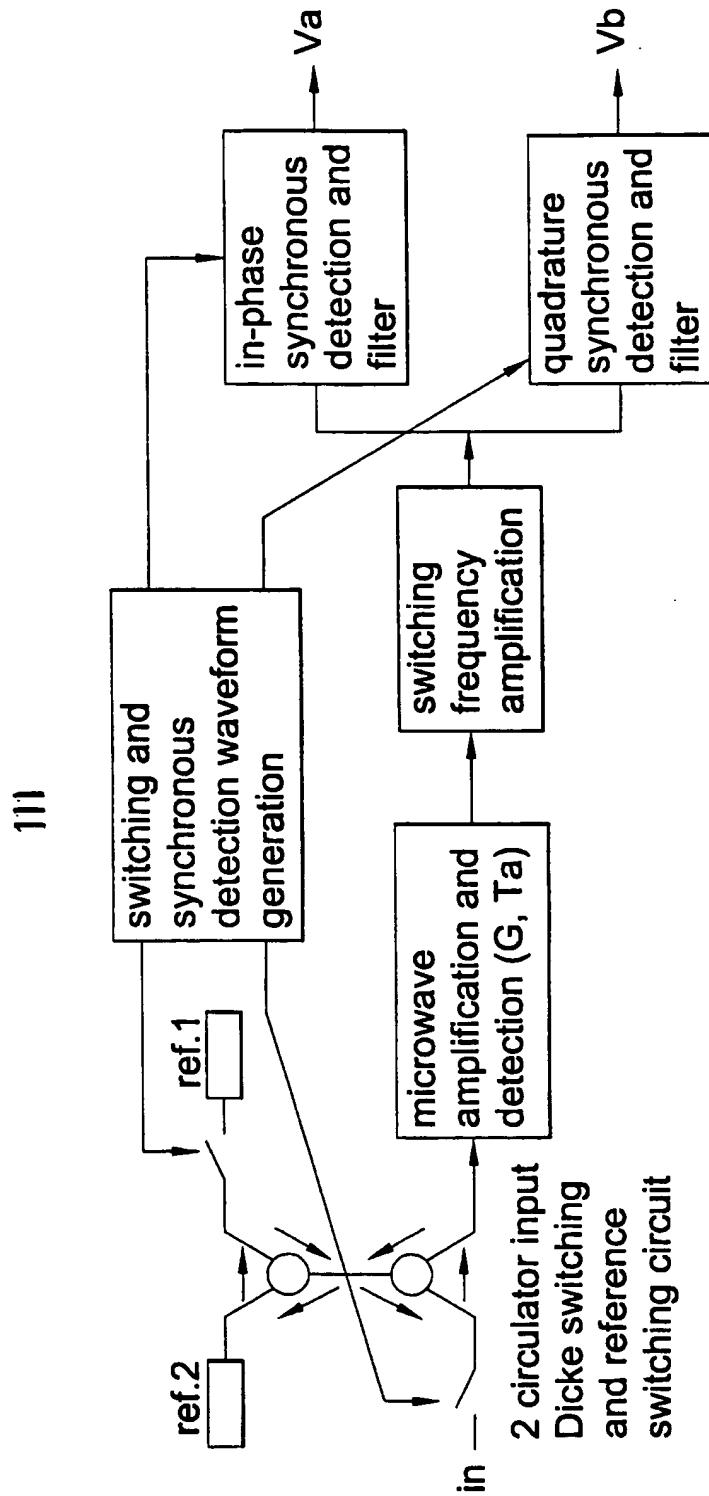


Fig. 4

5/6

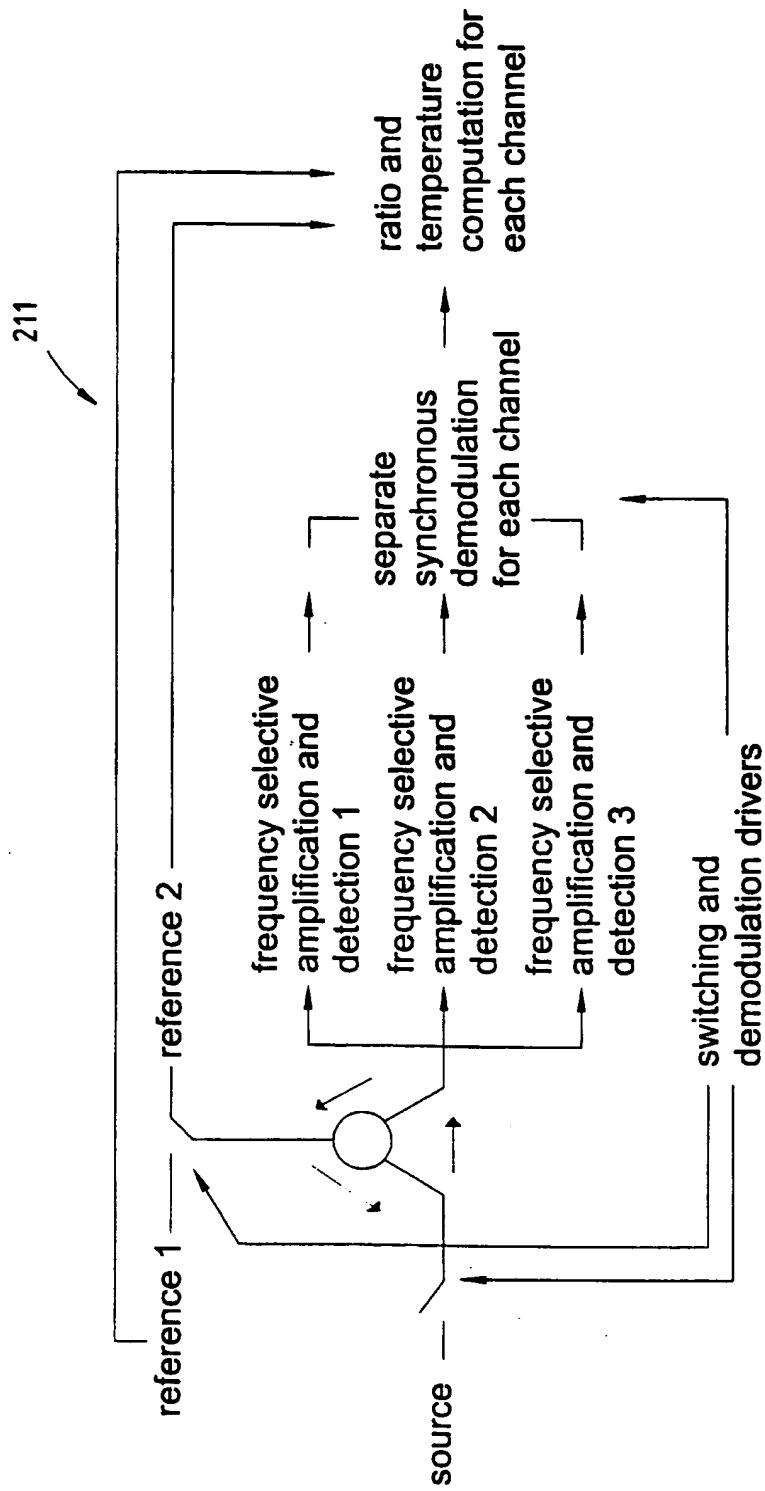


Fig. 5

6/6

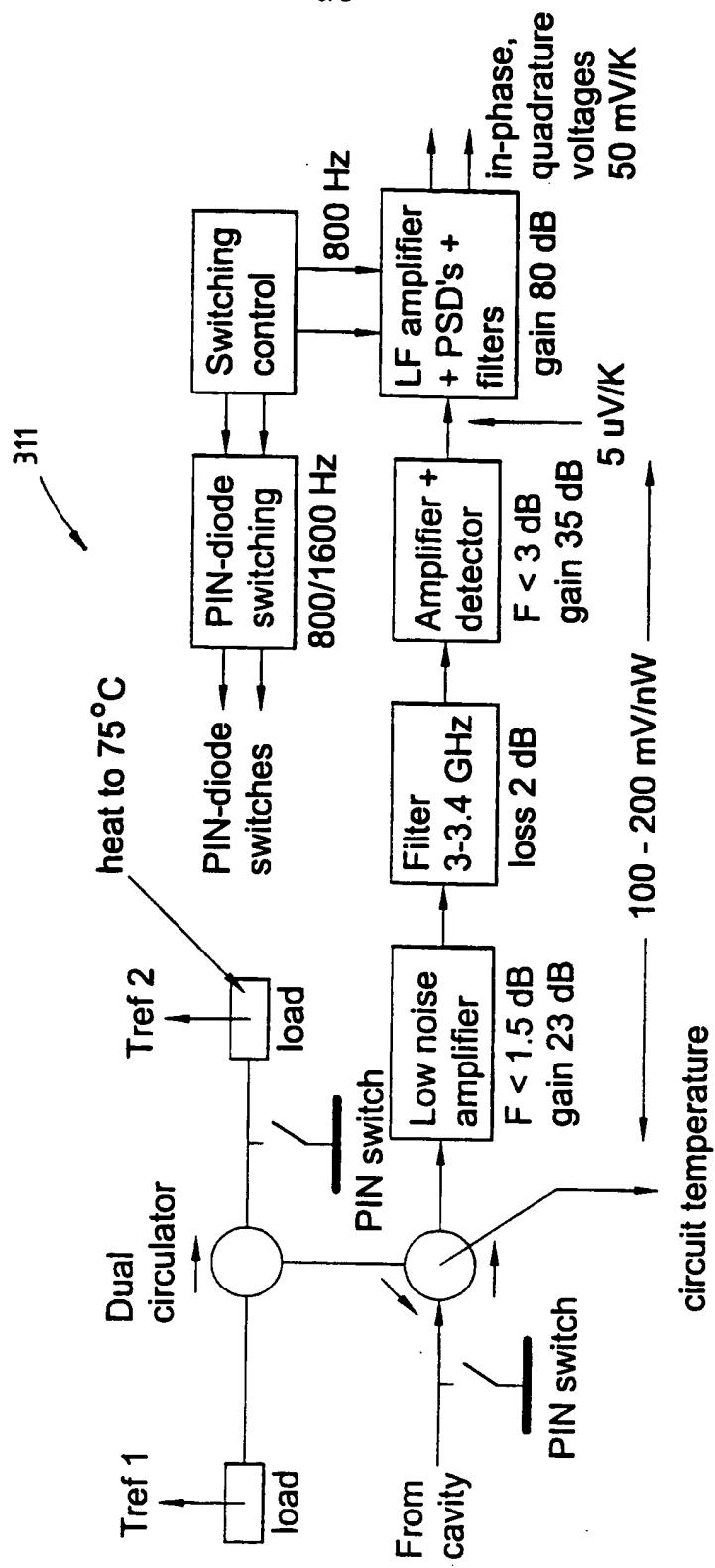


Fig. 6

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 01/01043

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01K11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 586 970 A (CONWAY WILLIAM H ET AL) 22 June 1971 (1971-06-22) the whole document ---	1-5, 11-14, 16-21,27
A	VANLOOT D ET AL: "NOUVEAU DISPOSITIF ELECTRONIQUE DE TRAITEMENT DU SIGNAL BASSE FREQUENCE DANS LES RADIOMETRES A USAGES MEDICAUX" ONDE ELECTRIQUE, FR, EDITIONS CHIRON S.A. PARIS, vol. 69, no. 5, 1 September 1989 (1989-09-01), pages 60-65, XP000066062 ISSN: 0030-2430 the whole document ---	1,6 -/-

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

° Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *&* document member of the same patent family

Date of the actual completion of the international search

20 April 2001

Date of mailing of the international search report

27/04/2001

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl.
Fax (+31-70) 340-3016

Authorized officer

Ramboer, P

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 01/01043

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 697 600 A (SADIS BRUKER SPECTROSPIN) 21 February 1996 (1996-02-21) the whole document ---	1,6,7, 29,35,36
A	GB 2 013 350 A (PHILIPS NV) 8 August 1979 (1979-08-08) the whole document ---	1,7,29, 35
A	EP 0 294 854 A (UNIV GLASGOW) 14 December 1988 (1988-12-14) the whole document -----	1-50

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/GB 01/01043

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 3586970	A	22-06-1971	NONE		
EP 0697600	A	21-02-1996	FR 2723784 A DE 69514169 D DE 69514169 T JP 3037882 B JP 8297055 A US 5741071 A US 5909963 A		23-02-1996 03-02-2000 24-08-2000 08-05-2000 12-11-1996 21-04-1998 08-06-1999
GB 2013350	A	08-08-1979	DE 2803480 A FR 2415799 A JP 1326214 C JP 54113381 A JP 60046648 B US 4235107 A		02-08-1979 24-08-1979 16-07-1986 04-09-1979 17-10-1985 25-11-1980
EP 0294854	A	14-12-1988	AT 46397 T AU 586949 B AU 1470188 A AU 573557 B AU 2314284 A CA 1253207 A DE 3479756 D DE 294854 T DK 10284 A DK 124691 A EP 0114094 A IE 55875 B IE 55876 B IL 70677 A IL 86104 A JP 59192925 A NZ 206774 A NZ 218636 A US 4627442 A ZA 8400063 A		15-09-1989 27-07-1989 21-07-1988 16-06-1988 19-07-1984 25-04-1989 19-10-1989 11-05-1989 13-07-1984 25-06-1991 25-07-1984 14-02-1991 14-02-1991 30-12-1988 31-03-1989 01-11-1984 27-11-1987 27-11-1987 09-12-1986 29-08-1984